SYNTHESIS OF POLY(ACRYLONITRILE-*co*-DIVINYLBENZENE-*co*-VINYLBENZYL CHLORIDE)-DERIVED HYPERCROSSLINKED POLYMER MICROSPHERES AND A PRELIMINARY EVALUATION OF THEIR POTENTIAL FOR THE SOLID-PHASE CAPTURE OF PHARMACEUTICALS

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Abstract

Poly(acrylonitrile (AN)-*co*-divinylbenzene (DVB)-*co*-vinylbenzyl chloride (VBC)) terpolymers were synthesized by precipitation polymerization in the form of porous polymer microspheres. The poly(AN-*co*-DVB-*co*-VBC) polymers were then hypercrosslinked, *via* a Friedel-Crafts reaction with $FeCl_3$ in nitrobenzene, to provide a significant uplift in the specific surface areas of the polymers. FT-IR spectra of the hypercrosslinked poly(AN-*co*-DVB-*co*-VBC)s showed that the chloromethyl groups derived from VBC were consumed by the Friedel-Crafts reactions, which was consistent

with successful hypercrosslinking. Hypercrosslinking installed a number of new, small pores into the polymers, as evidenced by a dramatic increase in the specific surface areas upon hypcrosslinking (from ~ 530 $m^2.g^{-1}$ to 1,080 $m^2.g^{-1}$). The hypercrosslinked polymers are very interesting for a range of applications, not least of all for solid-phase extraction (SPE) work, where the convenient physical form of the polymers (beaded format), their low mean particle diameters and narrow particle size distributions, as well as their high specific surface areas and polar character (arising from the acrylonitrile residues), make them attractive candidates as SPE sorbents. In this regard, in a preliminary study one of the hypercrosslinked polymers was utilized as an SPE sorbent for the capture of the polar pharmaceutical diclofenac from a polar environment.

Keywords

Polyacrylonitrile
Hypercrosslinked terpolymer
Diclofenac
Polar pharmaceuticals
UV absorption

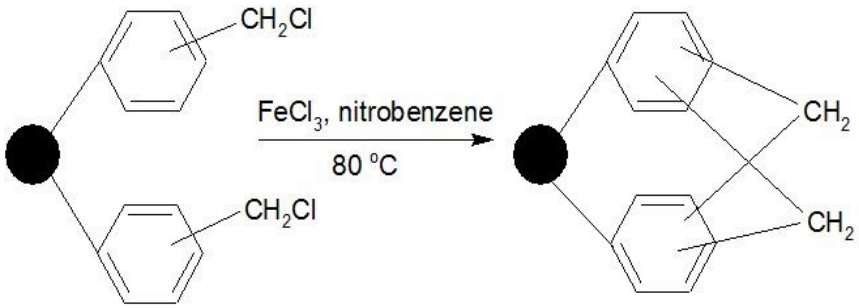
Introduction

The presence of pharmaceutical-derived compounds as low level contaminants in water has led to raised public concerns in recent years [1,2]. Pharmaceutical residues make their way into rivers, and other water courses, and have potentially toxic effects towards human and aquatic life [3]. Pharmaceuticals can be introduced into the environment through various routes, primarily through wastewater treatment plants (WWTPs) from housing

areas and from hospitals [4,5]. Pharmaceuticals in the sewage system can be degraded or removed, however some residues remain and are present in very low concentrations in surface waters, wastewater treatment plants (WWTPs), in hospitals influent and effluent, and drinking water [3,6]. Diclofenac, a non-steroidal anti-inflammatory drug, is one of the most extensively studied pharmaceuticals due to its potentially toxic effects and low biodegradability in WWTPs [7-9]. Al-Odaini *et al.* reported that 15 out of these 19 pharmaceutical residues (18 pharmaceuticals from six therapeutic classes and one metabolite) were detected in Langat River water samples, including diclofenac which was detected at high concentration (280.9 ng L^{-1}) [10].

The removal of pharmaceuticals from wastewater can be performed by sorption processes with selected sorbents. Sorbents are classified into silica-based, carbon-based and polymer-based sorbents. Polymeric sorbents have been the subject of particular interest and development due to their ability to overcome the disadvantages of silica-based and carbon-based sorbents in terms of chemical stability and porosity [11]. The silica-based materials were first chemically modified with C_8, C_{18}, phenyl, CN or NH_2 groups as sorbents for SPE processes [12]. Nonetheless, these silica-based sorbents present several drawbacks, including instability at extreme pHs and low recovery in the extraction of polar compounds [13]. It was also reported that activated carbon prepared from olive stones gave the highest sorption capacity for diclofenac from aqueous solutions, with maximum sorption at pH 2 [14]. However, activated carbon applications are limited because of their poor mechanical strength, low sorption capacity, low selectivity and incomplete regeneration [15]. Thus, hypercrosslinked (HXL) polymers become interesting as SPE

sorbents since they have high specific surface areas (above 1,000 $m^2.g^{-1}$) and tuneable chemistry, in combination with a high micropore content [16-18]. Hypercrosslinked polymers, first introduced by Davankov *et al.*, have a number of features that render them attractive for exploitation as SPE sorbents, with a number of recent publications focusing upon the preparation of hypercrosslinked polymers in appropriate physical formats and with ion-exchange groups to enable selective extractions [19]. The synthesis of HXL polymers is often based on Friedel-Crafts reactions with fast kinetics which install short, rigid bridges between adjacent phenyl rings resulting in a highly crosslinked network with high porosity (Scheme 1) [20,21]. Sherrington's group synthesized HXL materials from poly(divinylbenzene(DVB)-co-vinylbenzyl chloride(VBC)) precursors, where the chloromethyl ($-CH_2Cl$) substituent acts as an internal electrophile that leads to high specific surface areas up to ~1,200 $m^2.g^{-1}$ [22]. Hypercrosslinked polystyrene resins, based upon DVB and VBC comonomers, were prepared in a mixture of toluene and hexane; resins with high specific surface areas (up to 920 $m^2.g^{-1}$) were obtained [23,24]. Fontanals *et al.* synthesized high specific surface area sorbents by hyper-crosslinking precursor particles prepared from methacrylic acid (MAA), DVB and VBC. It was found that a poly(MAA-*co*-DVB-*co*-VBC) sorbent with a specific surface area up to 1125 $m^2.g^{-1}$ offered higher capacity and better selectivity in SPE than either of two commercially available materials evaluated [17].



Scheme 1. Schematic representation of Lewis acid catalyzed 'internal' hypercrosslinking reaction [25]

Acrylonitrile was incorporated into a terpolymer system to exploit the presence of nitrile group along polymer chains. For instance, nitrile groups in a poly(acrylonitrile-*co*-divinylbenzene-80) were modified chemically with hydroxylamine [26,27], hydrazine and ethanolamine, respectively to enhance the copolymer functionality as an active adsorbent to capture cationic species [27]. DVB comonomer was introduced into a terpolymer system as a crosslinker to create a crosslinked network for the PAN system. VBC comonomer was introduced to develop a hypercrosslinked 3D network that is able to provide high porosity and high micropore content.

Material and methods

Materials

The reagents used for the polymer synthesis were acrylonitrile (AN) (≥99% grade, Merck, Netherlands), divinylbenzene (DVB-80) (80% grade, Sigma-Aldrich, Dorset, UK) and 4-vinylbenzyl chloride (VBC) (90% grade, Sigma-Aldrich, Dorset, UK). The benzoyl peroxide (BPO) that was used as initiator was supplied by Sigma-Aldrich (Dorset, UK)

and purified by recrystallization from acetone (≥99% grade) (Sigma-Aldrich, UK) at low temperature. Acetonitrile (HPLC grade), toluene (≥99% grade) and methanol (≥99% grade) were supplied by Sigma-Aldrich (Dorset, UK). Nitrobenzene (>99% grade) (Sigma-Aldrich) and iron(III) chloride (Fisher, US) were used as reagents in hypercrosslinking reactions. Diclofenac was supplied by Sigma-Aldrich (Dorset, UK). Acrylonitrile, divinylbenzene and vinylbenzyl chloride were purified by passing them through a short column of neutral alumina. All other reagents were used as received.

Equipment

Polymerizations were performed in Nalgene® plastic bottles. The bottles were placed in a Stuart Scientific S160 incubator (Surrey, UK) on a Stovall low profile roller (Essex, UK) system.

Precipitation polymerizations

The monomers (DVB-80, AN and VBC), at a total monomer concentration of 2% (w/v) relative to the total volume of solvent, and initiator (BPO) (at a concentration of 2% (w/w) relative to the total monomer mass) were dissolved in a mixture of acetonitrile and toluene in a polypropylene Nalgene® bottle fitted with a screw cap. **Table 1** details the ratios and amounts of monomers used for a total volume of solvent of 200 mL (150 mL acetonitrile and 50 mL toluene).

Table 1. Ratios and volumes of monomers in the feed for the synthesis of polymers in a mixture of acetonitrile and toluene

Sample	Reaction time, h	AN, mol%	DVB-80, mol%	VBC, mol%	AN, mL	DVB-80, mL	VBC, mL
P12	48	-	100	-	-	4.300	-
P08	48	25	70	5	0.585	3.560	0.252
P09	48	20	75	5	0.454	3.687	0.244
P13	96	20	75	5	0.454	3.687	0.244
P16	96	25	70	5	0.585	3.560	0.252
P17	48	100	-	-	4.938	-	-

The monomer solution was deoxygenated by sparging with N_2 in an ice bath for 30 minutes. After resealing, the bottle was placed on a low profile roller and rotated slowly (30 rpm) about its long axis in an incubator. The temperature of the incubator was increased from ambient to 60 ˚C over a period of around two hours, and the polymerization allowed to proceed for a further 46 hours. After this time, the particles that formed were filtered on a 0.22 μm nylon membrane filter and then washed in sequence with 15 mL volumes of acetonitrile, toluene, methanol and acetone. After washing, the polymer sample was dried in a vacuum oven at 40 ˚C overnight.

The conversion of poly(AN), poly(DVB-80) and terpolymers was calculated using Equation [1].

$$Monomer\ conversion = \frac{Weight\ of\ polymers\ (g)}{Monomer\ feed\ (g)} \times 100 \quad [1]$$

Hypercrosslinking reactions

Poly(AN-*co*-DVB-80-*co*-VBC) (1.0 g) and 30 mL of nitrobenzene were added to a 100 mL three-necked, round-bottomed flask. The mixture was then purged with N_2 at room temperature for 1 hour. Iron (III) chloride ($FeCl_3$) in nitrobenzene (20 mL) was added and the mixture was heated at 80 ˚C for 18 hours. The hypercrosslinked particles were recovered and washed several times with methanol. The particles were then extracted overnight with acetone in a Soxhlet extractor and were washed again with methanol before drying in a vacuum oven at 40 ˚C.

Batch adsorption of pharmaceuticals

25 mg of diclofenac standard was weighed and transferred into a volumetric flask. Methanol was then added to give a 250 mL solution (100 ppm diclofenac).

A series of diclofenac solutions (10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 ppm) were prepared by diluting the standard stock solution with methanol, for the preparation of a calibration curve. These solutions were scanned using a UV-Vis spectrophotometer in the range 200-400 nm. A graph of absorbance against concentration of diclofenac was plotted to determine the gradient. The effect of diclofenac concentration on sorption was analysed by adding 5 mg samples of hypercrosslinked poly(AN-*co*-DVB-*co*-VBC) into ten different centrifuge tubes containing 20, 40, 60, 80, 100, 120, 140, 160, 180 and 200 ppm aqueous diclofenac solutions, respectively. The effect of pH was analysed by adding 5 mg samples of hypercrosslinked poly(AN-*co*-DVB-80-*co*-VBC) into five different centrifuge tubes containing 20 ppm aqueous diclofenac solutions; the pH of the solutions was adjusted to

pH 3, 5, 7, 9 and 11, respectively, using NaOH (1 M) and HCl (1 M) aqueous solutions. All the samples were left to equilibrate overnight prior to analysis. Then, the samples were centrifuged for five minutes at 4,800 rpm. 3 mL aliquot of supernatant were taken out and analyzed by UV-Vis in the range 200-400 nm.

Determination of adsorption capacity

The adsorption capacity was determined by using Equation [2], taking into account the concentration difference of the diclofenac solution at the beginning and at equilibrium.

$$q_{e=\frac{(C_o-C_e)V}{m}} \qquad [2]$$

Where C_o and C_e are the initial and the equilibrium diclofenac concentration mg/L, respectively, V is the volume of solution (mL) and m is the amount of adsorbent used (g). The removal percentage can be calculated as:

$$\text{Removal percentage} = \frac{C_o-C_e}{C_o} \times 100 \qquad [3]$$

Characterizations

Fourier Transform Infra-red (FT-IR) spectroscopy

Fourier Transform Infrared spectra were recorded using a Spectrum BX Perkin Elmer (United States) with Universal Attenuated Total Reflectance (UATR) technique to identify the functional groups in the polymers. Samples were measured in the range 280 cm^{-1}-4000 cm^{-1} at 25 ˚C.

Elemental microanalysis

Carbon, hydrogen and nitrogen contents were determined using a Perkin Elmer 628 Series instrument at the Material Characterization Laboratory at the Faculty of Engineering, UPM. The samples were wrapped in tin foil and combusted at 1800 ˚C in pure oxygen. The combustion products were catalyzed and interferences removed before being swept into a detector zone where each element was separated and eluted as CO_2, H_2O and NO_2. The signals were converted to a percentage of elements.

Scanning Electron Microscopy (SEM)

Scanning electron microscopy (JEOL JSM 6360LA, Japan) was used to observe the morphology of the polymer particles produced. A steel stub was coated with conductive copper using double-sided adhesive tape. A thin layer of sample was then deposited onto the coated steel stub. Platinum coating of the immobilized sample was carried out for 8 minutes. A coated sample was placed inside the SEM chamber and a vacuum was applied. Micrographs were acquired at accelerating voltages of 10.0 kV or 25.0 kV. The microsphere diameters and particle size distributions were calculated using ImageJ software from the SEM image analysis of 100 individual particles [28].

Nitrogen sorption analysis

The specific surface areas, specific pore volumes and mean pore sizes of polymer microspheres were determined using a Micrometrics ASAP 2010 (United States) surface area analyzer. Samples were degassed overnight under vacuum at 100 ˚C and then analyzed using nitrogen sorption carried out at 77 K.

Ultraviolet visible (UV-Vis) spectrophotometry

A 1601 Shimadzu (Japan) double beam UV-Visible spectrophotometer was used for UV-Vis measurements, with methanol as solvent.

Results and Discussion

Yields of polymerization

For the precipitation polymerizations to give poly(DVB-80) and poly(AN-*co*-DVB-80-*co*-VBC), it was observed that the initial homogeneous solutions of monomers and initiator in the Nalgene bottles started to form milky, white suspensions of particles after 90 to 120 minutes of reaction time. However, the nucleation of poly(AN) particles could not be observed. **Table 2** shows the yields of poly(AN), poly(DVB-80) and poly(AN-*co*-DVB-80-*co*-VBC) isolated after 48 hours and 96 hours of reaction time. The yields of poly(AN-*co*-DVB-80-*co*-VBC) after 48 hours of reaction time were between 36-38%. The yields of poly(AN) and poly(DVB-80) were 21% and 37%, respectively. Lower yields of poly(AN) are to be expected due to the absence of crosslinking monomer (DVB-80) which is responsible for the entropic precipitation of particles [11].

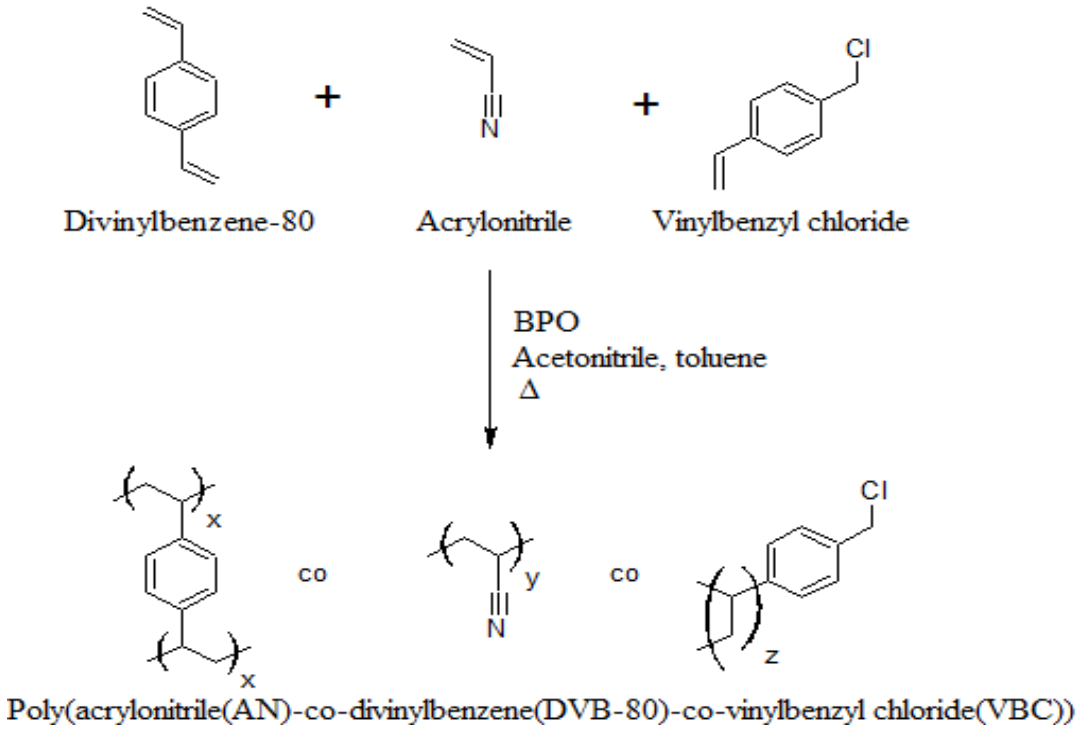
The yields of poly(AN-*co*-DVB-80-*co*-VBC) isolated after 96 hours of reaction time were generally higher, and were between 60% to 61% compared to the yields of poly(AN-*co*-DVB-80-*co*-VBC) (36% to 38%) obtained after 48 hours. These results show that neither all monomer nor all initiator is consumed within the first 48 hours; the half-life of benzoyl peroxide (BPO) is one hour at 92 ˚C (and one minute at 131 ˚C) [29]. In comparison, 2,2'-azobisisobutyronitrile (AIBN), which is often used as initiator for

precipitation polymerizations, has a half-life of one hour at 85 ˚C (and five hours at 70 ˚C), thus BPO decomposes more slowly than AIBN.

Table 2. Yields of poly(AN), poly(DVB-80) and poly(AN-*co*-DVB-80-*co*-VBC) synthesised in a mixture of acetonitrile/toluene for 48 hours and 96 hours.

Sample	AN/DVB-80/VBC, mol%	Yields, %	
		48 h reaction time	96 h reaction time
P12	0/100/0	37	-
P09	20/75/5	38	-
P08	25/70/5	36	-
P17	100/0/0	21	-
P13	20/75/5	-	60
P16	25/70/5	-	61

The reaction of scheme for synthesis of poly(AN-*co*-DVB-80-*co*-VBC) is shown in **Scheme 2**.



Scheme 2. Synthesis of poly(acrylonitrile-*co*-divinylbenzene-80-*co*-vinylbenzyl chloride)

Fourier Transform Infrared (FT-IR) analysis

Figure 1 shows the FT-IR spectra of poly(AN) and poly(DVB-80), respectively. The FT-IR spectrum of poly(AN) shows a strong absorption band at 2244 cm^{-1} which corresponds to the stretching vibration of the nitrile groups. The absorption band at 2928 cm^{-1} is assigned to aliphatic C-H stretches. The peak at 1449 cm^{-1} is related to the bending vibration of $–CH_2$ groups. The FT-IR spectrum of poly(DVB-80) shows a band at 1597 cm^{-1} that corresponds to the C=C stretching vibrations from aromatic rings. The band at 1443 cm^{-1} is assigned to the bending vibrations of aliphatic $–CH_2$ groups [30].

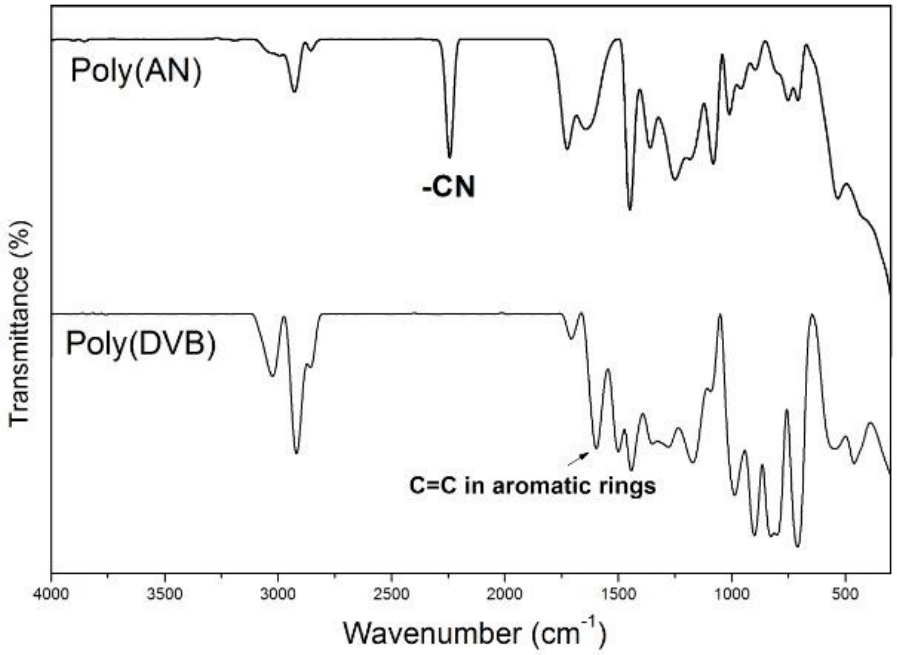
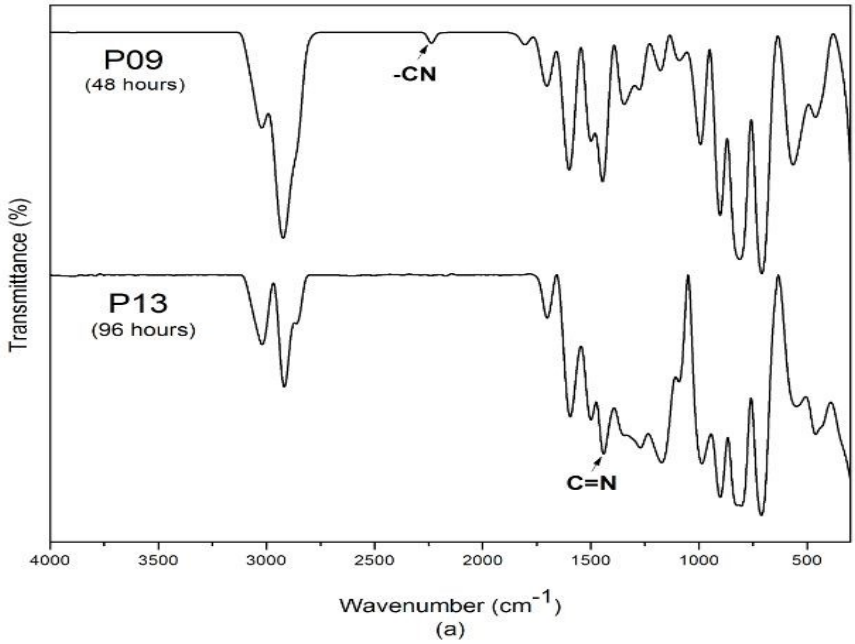


Figure 1. FT-IR spectra of polyacrylonitrile (poly(AN)) and polydivinylbenzene (poly(DVB-80))

Figure 2a and **Figure 2b** show the FT-IR spectra of poly(AN-*co*-DVB-80-*co*-VBC) that were isolated after 48 hours and 96 hours of reaction time, respectively. The FT-IR spectra of P09 and P08 (that were isolated after 48 hours) show an absorption band at ~2240 cm^{-1} assigned to the CN stretching vibration of the AN unit thereby confirming the AN incorporation. The intensity of the CN band increased as the amount of AN (mol%) in the monomer feed was increased. However, the absorption band assigned to the CN stretching vibration was not present in the spectra of P13 and P16, polymers that were isolated after 96 hours of reaction. The absorption band that is assigned to the stretching vibration of C=N at ~1440 cm^{-1} was more intense in the case of poly(AN-*co*-DVB-80-*co*-VBC) that was isolated after 96 hours compared to the intensity of C=N absorption band in

poly(AN-co-DVB-80-*co*-VBC) that was isolated after 48 hours. The presence of C-Cl wagging band observed at ~1270 cm^{-1} [31] confirms the inclusion of the VBC comonomer.



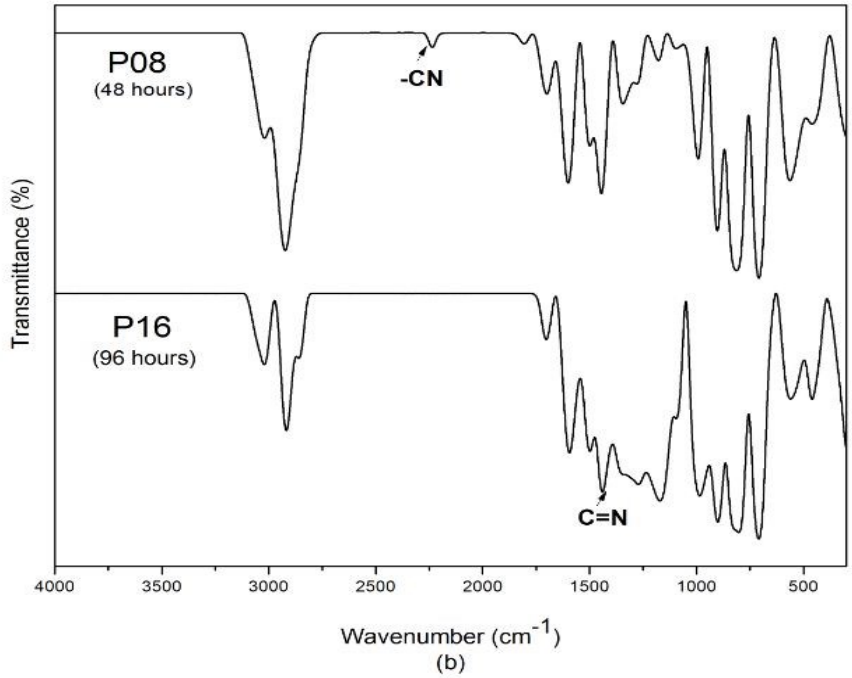
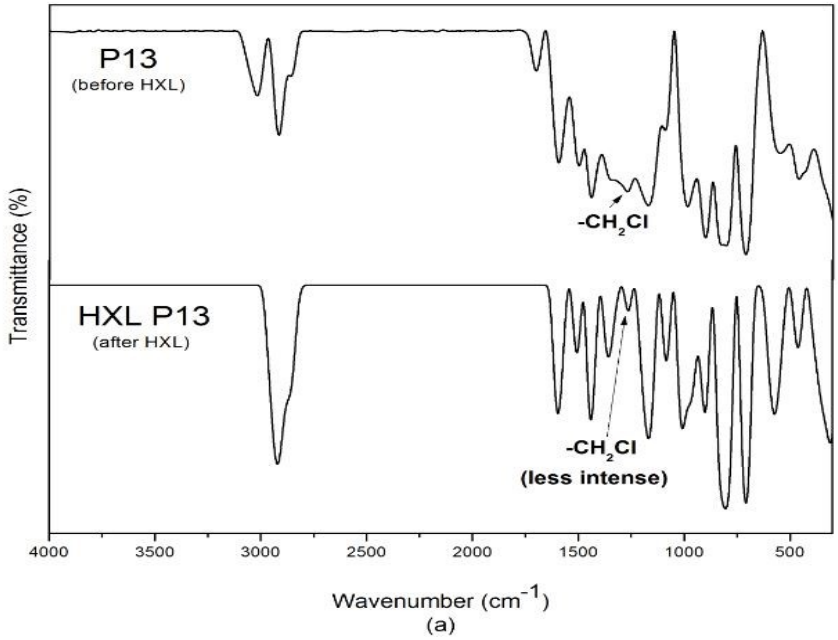


Figure 2. FT-IR spectra of (a) poly(AN-*co*-DVB-80-*co*-VBC) 20/75/5 and (b) poly(AN-*co*-DVB-80-*co*-VBC) 25/70/5 terpolymers that were isolated after 48 h and 96 h of reaction time, respectively.

The FT-IR spectra of the poly(AN-*co*-DVB-80-*co*-VBC) terpolymers before and after the hypercrosslinking reactions are shown in **Figure 3a** and **Figure 3b**. The absorption band at ~1270 cm^{-1}, which is assigned to the chloromethyl groups, is present in all poly(AN-*co*-DVB-80-*co*-VBC) FT-IR spectra, however this band almost disappears following hypercrosslinking as a result of the consumption of chloromethyl groups through hypercrosslinking.



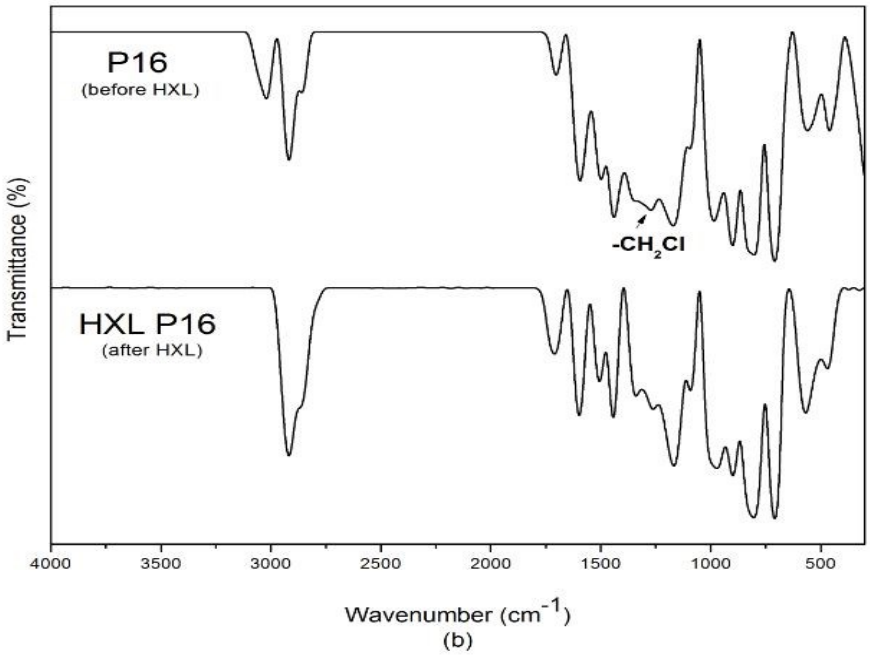


Figure 3. FT-IR spectra of (a) poly(AN-*co*-DVB-80-*co*-VBC) 20/75/5 and (b) poly(AN-*co*-DVB-80-*co*-VBC) 25/70/5 terpolymers before and after hypercrosslinking reaction.

Elemental microanalysis

Elemental microanalysis was used to estimate the composition of the polymers isolated from the precipitation polymerizations and to monitor the hypercrosslinking reactions. **Table 3** shows the C, H and N contents of poly(AN), poly(DVB) and poly(AN-*co*-DVB-80-*co*-VBC) polymers before and after hypercrosslinking reactions. As expected, P17 poly(AN) contains the highest N content since this an AN homopolymer and there are no comonomers. At the other extreme of composition, poly(DVB-80) (P12) contains 0% N since no AN was present in the feed. In the case of P13 and P16, the N contents increased from 2.4% to 2.8% as the mol% of AN was increased in the monomer feed. The N

contents of HXL P13 and HXL P16 were 2.4% and 3.0%, respectively, which is in agreement with their expected N contents.

Table 3. Elemental microanalysis data of poly(DVB-80), poly(AN) and poly(AN-*co*-DVB-80-*co*-VBC) before and after hypercrosslinking (HXL) reactions.

Sample	Mole fraction of AN/DVB80/VBC, %	Elemental microanalysis, %					
		C		H		N	
		Expected	Found	Expected	Found	Expected	Found
P12	0/100/0	91.6	88.3	8.0	7.8	0.3	0.2
P13	20/75/5	88.6	87.9	7.4	7.5	2.4	2.4
P16	25/70/5	87.9	86.0	7.4	7.4	3.1	2.8
HXL P13	20/75/5	90.0	87.6	7.6	7.5	2.4	2.4
HXL P16	25/70/5	89.4	87.2	7.5	7.7	3.1	3.0
P17	100/0/0	67.9	66.7	5.7	5.7	26.4	26.3

Scanning Electron Microscopy (SEM) analysis

The polymers were imaged using SEM. As shown in **Figure 4a**, poly(AN) appears as an agglomerated clusters of small particles. Meanwhile, poly(DVB-80) is in the form of spherical particles (beads) (**Figure 4b**).

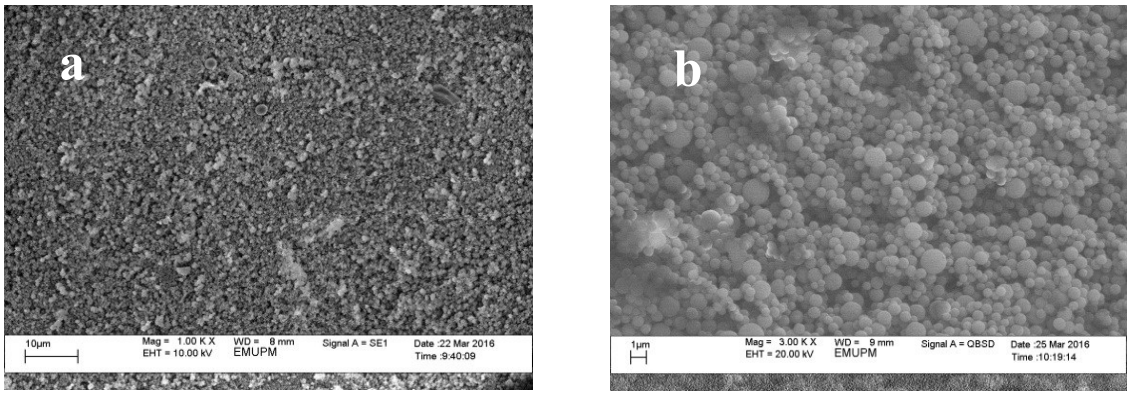


Figure 4. SEM micrographs of (a) poly(AN) and (b) poly(DVB-80)

Figure 5a and **Figure 5c** show the morphologies of poly(AN-*co*-DVB-80-*co*-VBC) before hypercrosslinking reactions. The terpolymer particles are nearly perfect polymer microspheres, and **Figure 5b** and **Figure 5d** show that the spherical form of the polymers is retained through the hypercrosslinking reactions.

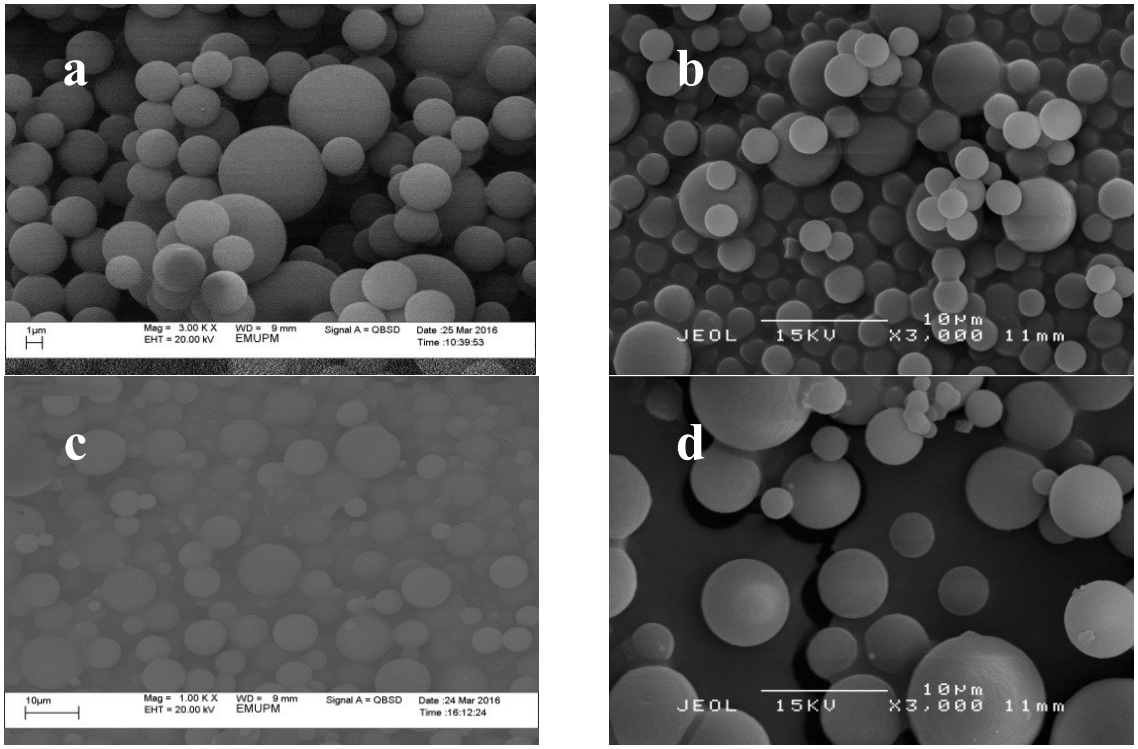


Figure 5. SEM micrographs of (a) P13 (b) HXL P13 (c) P16 and (d) HXL P16

As shown in **Table 4**, the mean particle diameter of the poly(AN-*co*-DVB-*co*-VBC) (3.9 μm (P13) and 4.6 μm (P16)) increased to 4.2 μm (HXL P13) and 6.6 μm (HXL P16), respectively, after hypercrosslinking. The C_v values indicate that both poly(AN-*co*-DVB-*co*-VBC) and HXL poly(AN-*co*-DVB-*co*-VBC) were polydisperse (C_v value above 15%).

Table 4. Particle size of poly(AN), poly(DVB-80) and poly(AN-*co*-DVB-80-*co*-VBC) before and after HXL reaction

Sample	AN/DVB-80/VBC, mol%	Mean particle diameter, μm	Coefficient of variation, %	Dispersity
P12	0/100/0	1.3	22	Polydisperse
P13	20/75/5	3.9	25	Polydisperse
P16	25/70/5	4.6	31	Polydisperse
HXL P13	20/75/5	4.2	27	Polydisperse
HXL P16	25/70/5	6.6	17	Polydisperse
P17	100/0/0	Agglomerated clusters	-	-

Brunauer-Emmett-Teller (BET) surface area analysis

The porosity of the polymers isolated from the precipitation polymerizations and their hypercrosslinked variants were determined using nitrogen sorption analysis and application of BET theory. **Table 5** shows the nitrogen sorption analysis data obtained for poly(AN-*co*-DVB-80-*co*-VBC) before and after hypercrosslinking reactions.

Table 5. BET data of poly(AN), poly(DVB-80) and poly(AN-*co*-DVB-80-*co*-VBC) terpolymers before and after hypercrosslinking

Sample	AN/DVB-80/ VBC, mol%	Specific surface area, $m^2.g^{-1}$	Specific pore volume, $cm^3.g^{-1}$	Mean pore size, nm
P12	0/100/0	932	0.375	2.2
P13	20/75/5	528	0.412	3.1
P16	25/70/5	730	0.659	3.6
HXL P13	20/75/5	1078	0.806	2.9
HXL P16	25/70/5	1071	1.083	4.0
P17	100/0/0	2	-	-

As shown in **Table 5**, and as expected, P12 has high specific surface area (932 $m^2.g^{-1}$) due to the inclusion of DVB-80 alone as monomer. P13 and P16 had 75 and 70 mol% of DVB-80 in the monomer feed, respectively, and had lower specific surface areas (528 $m^2.g^{-1}$ and 730 $m^2.g^{-1}$, respectively) than the poly(DVB). The mean pore size of P13 and P16 were similar to one another, at ~3.4 nm, and their specific pore volumes were in the range of 0.412 to 0.659 $cm^3.g^{-1}$. Upon hypercrosslinking, the BET specific surface areas increased significantly up to 1,078 $m^2.g^{-1}$ (HXL P13) and 1,071 $m^2.g^{-1}$ (HXL P16). The specific pore volume was also increased in the range of 0.806 $cm^3.g^{-1}$ to 1.083 $cm^3.g^{-1}$.

Uptake of pharmaceutical by polymers - Ultraviolet (UV) adsorption analysis

Effect of concentration

Figure 6 shows the effect of concentration on the adsorption of a polar analyte (diclofenac). The percentage uptake of diclofenac by HXL poly(AN-*co*-DVB-80-*co*-VBC) at various concentrations increase significantly as the concentration of diclofenac is increased. **Figure 6** shows that the diclofenac uptake increased from 75% (29.8 $mg.g^{-1}$ of adsorption capacity) to 95% (303.0 $mg.g^{-1}$ of adsorption capacity). The equilibrium point is reached at around 180-200 ppm of diclofenac concentrations.

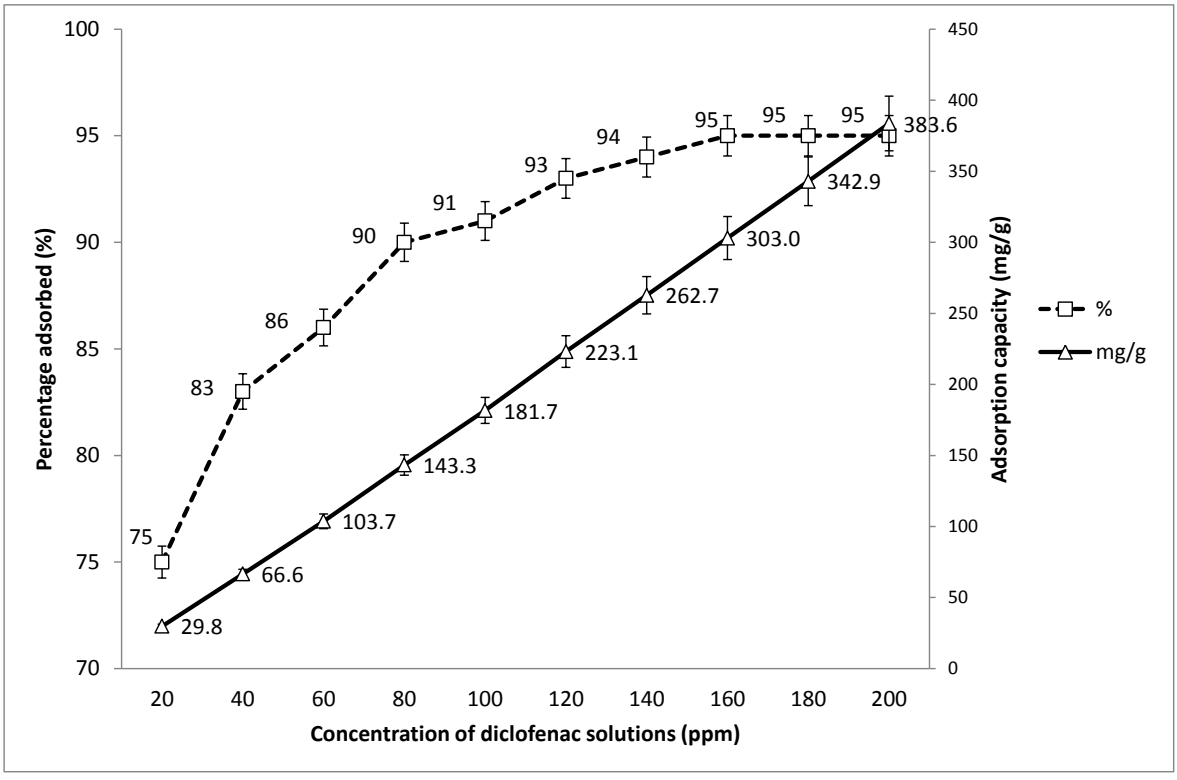


Figure 6. Adsorption capacity of HXL poly(AN-*co*-DVB-80-*co*-VBC) at different concentrations of diclofenac

Condition: 5 mg of hypercrosslinked poly(AN-*co*-DVB-*co*-VBC) in 10 ml of different concentrations (20-200 ppm) of diclofenac solution at 4800 rpm for 24 h at room temperature of 25 °C.
(Error bars represent the standard deviations of triplicate recordings)

Effect of pH

The effect of pH was investigated to study the influence of pH towards adsorption capacity of diclofenac onto the surface of HXL poly(AN-*co*-DVB-80-*co*-VBC). In addition, diclofenac has certain percentage of ionisation under certain pH. **Figure 7** shows the effect of pH on the adsorption of HXL poly(AN-*co*-DVB-80-*co*-VBC) towards diclofenac in the pH range of 3-11. The results show that adsorptions of diclofenac onto the surface of polymeric material were increased as the pH was increased from pH 3 to 7 (adsorption capacity of 25.4 $mg.g^{-1}$, 26.0 $mg.g^{-1}$ and 32.3 $mg.g^{-1}$ at pH 3, 5 and 7, respectively). Diclofenac is a weak acid with the pK_a value of 4.1 [32,33] and weakly ionized at low pH. Diclofenac displays hydrophobicity character in its less ionized form [33]. Therefore, hydrophobic interaction and hydrogen bonding might have facilitated the interaction of diclofenac with the surface of HXL poly(AN-*co*-DVB-80-*co*-VBC) in the pH range of 3-7.

As the pH of adsorption medium was increased to pH 9 and 11, the adsorptions of diclofenac were significantly decreased (30.7 $mg.g^{-1}$ and 29.9 $mg.g^{-1}$ at pH 9 and pH 11, respectively). This is due to the acidic diclofenac that was fully ionized at higher pH and the carboxyl group of diclofenac became negatively charged [32]. Thus, diclofenac was not readily available to interact with the surface of HXL poly(AN-*co*-DVB-80-*co*-VBC) and

consequently decreased its adsorption capacity. Another possible explanation is, electrostatic repulsive interactions might have occurred between diclofenac and HXL poly(AN-*co*-DVB-80-*co*-VBC) at high pH that consequently reduced their binding affinity [32]. This study shows that pH may give a significant effect on the adsorption of diclofenac onto the surface of hypercrosslinked poly(AN-*co*-DVB-80-*co*-VBC) adsorbent.

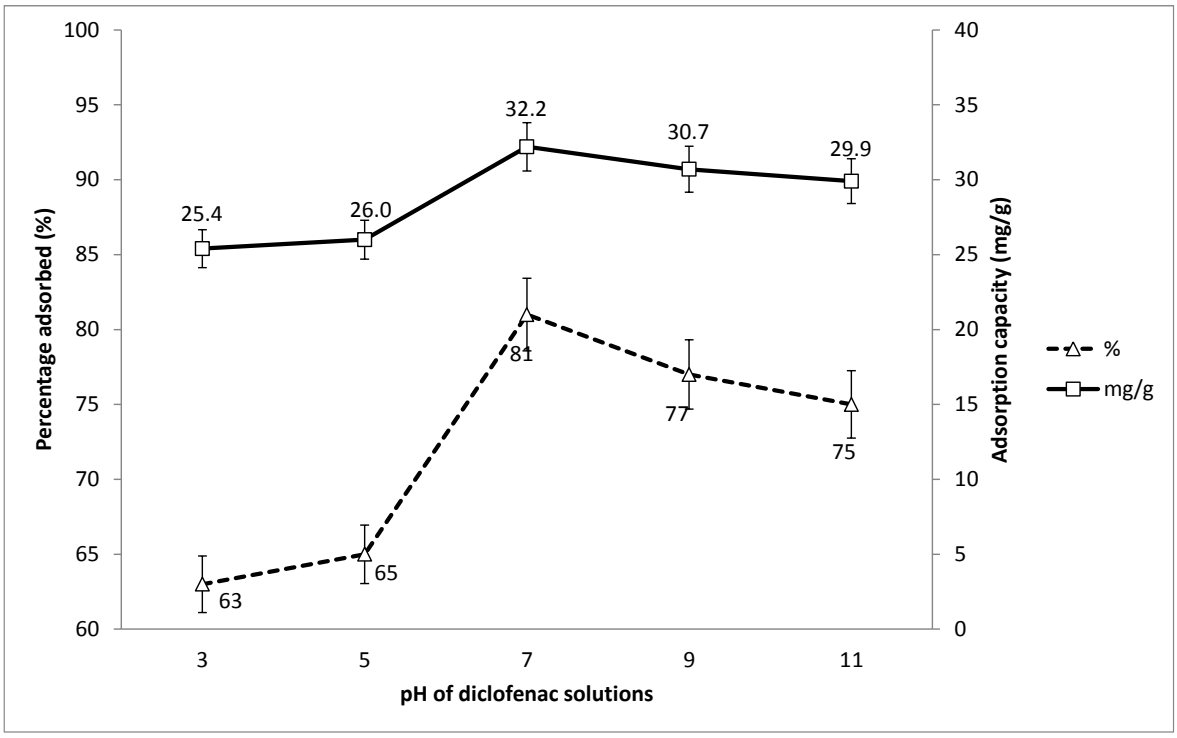


Figure 7. Adsorption capacity of HXL poly(AN-*co*-DVB-80-*co*-VBC) at different pH values

Condition: 5 mg of hypercrosslinked poly(AN-*co*-DVB-*co*-VBC) in 10 ml of 20 ppm diclofenac solution at 4800 rpm for 24 h at room temperature of 25 °C.
(Error bars represent the standard deviations of triplicate recordings)

4. Conclusions

Poly(AN-*co*-DVB-80-*co*-VBC) terpolymers were synthesized successfully *via* precipitation polymerisation using variable ratios of AN/DVB/VBC (mol%), and obtained in the form of porous polymer microspheres. Poly(AN-*co*-DVB-80-*co*-VBC) 35/60/5 (mol%), isolated after a reaction time of 96 hours, was obtained in the highest yield (64%). Hypercrosslinking of poly(AN-*co*-DVB-80-*co*-VBC) terpolymer with $FeCl_3$ *via* a Friedel-Crafts reaction gave rise to a significant increase in the specific surface areas without any compromise to the physical form of the polymer particles. The HXL poly(AN-*co*-DVB-80-*co*-VBC) had specific surface areas up to 1078 $m^2.g^{-1}$ and a maximum pore size at 4.0 nm. These highly porous polymers with polar character arising from the inclusion of acrylonitrile residues are attractive candidates as novel sorbents for solid-phase extraction work. In this regard, in a preliminary study a hypercrosslinked poly(AN-*co*-DVB-80-*co*-VBC) terpolymer was used to capture the polar pharmaceutical diclofenac from solution.

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Conflicts of Interest

The authors declare that they have no conflict of interest.

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Scheme Captions

Scheme 1 Schematic representation of Lewis acid catalyzed 'internal' hypercrosslinking reaction.

Scheme 2 Synthesis of poly(acrylonitrile-*co*-divinylbenzene-80-*co*-vinylbenzyl chloride).

Figure Captions

Figure 1 FT-IR spectra of polyacrylonitrile (poly(AN)) and polydivinylbenzene (poly(DVB-80)).

Figure 2 FT-IR spectra of (a) poly(AN-*co*-DVB-80-*co*-VBC) 20/75/5 and (b) poly(AN-*co*-DVB-80-*co*-VBC) 25/70/5 terpolymers that were isolated after 48 h and 96 h of reaction time, respectively.

Figure 3 FT-IR spectra of (a) poly(AN-*co*-DVB-80-*co*-VBC) 20/75/5 and (b) poly(AN-*co*-DVB-80-*co*-VBC) 25/70/5 terpolymers before and after hypercrosslinking reaction.

Figure 4 SEM micrographs of (a) poly(AN) and (b) poly(DVB-80).

Figure 5 SEM micrographs of (a) P13 (b) HXL P13 (c) P16 and (d) HXL P16.

Figure 6 Adsorption capacity of HXL poly(AN-*co*-DVB-80-*co*-VBC) at different concentrations of diclofenac.

Figure 7 Adsorption capacity of HXL poly(AN-*co*-DVB-80-*co*-VBC) at different pH values.

Table Captions

Table 1 Ratios and volumes of monomers in the feed for the synthesis of polymers in a mixture of acetonitrile and toluene.

Table 2 Yields of poly(AN), poly(DVB-80) and poly(AN-*co*-DVB-80-*co*-VBC) synthesised in a mixture of acetonitrile/toluene for 48 hours and 96 hours.

Table 3 Elemental microanalysis data of poly(DVB-80), poly(AN) and poly(AN-*co*-DVB-80-*co*-VBC) before and after hypercrosslinking (HXL) reactions.

Table 4 Particle size of poly(AN), poly(DVB-80) and poly(AN-*co*-DVB-80-*co*-VBC) before and after HXL reaction.

Table 5 BET data of poly(AN), poly(DVB-80) and poly(AN-*co*-DVB-80-*co*-VBC) terpolymers before and after hypercrosslinking.